TITLE: HIGH INTENSITY LINEAR ACCELERATOR DEVELOPMENT TOPICS FOR PANEL DISCUSSION ON "NUCLEAR ENERGY RESEARCH AND ACCELERATORS—FUTURE PROSPECTS"

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High Intensity Linear Accelerator Development Topics
for Panel Discussion on
" Nuclear Energy Research and Accelerators - Future Prospects"*

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Two companion papers at this meeting have introduced the subject of high intensity linacs for materials research and for radioactive waste transmutation; Prof. Kaneko's paper "Intense Proton Accelerator", and my paper "Accelerator-Based Intense Neutron Source for Materials R&D". I will expand on those remarks to briefly outline some of the extensive work that has been done at Los Alamos toward those two application areas, plus a third -- the production of tritium in an accelerator-based facility (APT - Accelerator Production of Tritium).

As discussed in Ref. 8 of my other paper, we have considered the provision of one ampere of deuterons in modules of 250 mA apiece, a current that represents about the upper limit of capacity in a 350 MHz deuteron drift-tube-linac (DTL) structure under a reasonable constraint set. This design uses two 125 mA, 175 MHz RFQ accelerators from the injectors up to an energy of 3 MeV, again because of the current limitation of a single channel in this energy range. The two RFQ outputs are funneled into the doubled-frequency DTL. The energy-selective and other features discussed in the ESNIT paper could be applied to this large machine also.

In the area of radioactive waste transmutation, we have been following the work of JAERI with great interest to understand the requirements on the accelerator. Our work on tritium production, however, has advanced to the stage of a rather complete scoping study and pre-conceptual design[1] for a cw machine comprised of two 350 MHZ, 125 mA RFQs up to 2.5 MeV, with 350 MHz DTLs following them up to 20 MeV, and then funneling into a 700 MHZ, 250 mA coupled-cavity-linac (CCL) for acceleration to the final energy of 1.6 GeV. (Fig. 1) This study was reviewed by the Energy Research Advisory Board of the US DOE in October 1989.

The APT machine could also be used to provide the 250-300 mA continuous beam required to transmute radioactive waste solely with

spallation neutrons; since providing high current in a linac is the challenge (whereas going to higher energy is easy), the machine can readily be scaled down to the 10-20 mA requirement for a hybrid system of accelerator plus multiplying target.

It is important to note that the physics and engineering design technology for such intense machines is in hand and a considerable body of experimental verification exists, but such a system has not been constructed and operated as a whole. Our confidence is such that we have costed and are proposing a staged development for APT, with the first stage being a four-year (minimum) construction of a 40 MeV, 125 mA cw prototype. Other components of this development program would include target/lattice experiments, development of a high-efficiency 700 MHz rf source, demonstration of the nonlinear beam expander, and tritium processing and systems studies.

The facility components are outlined in another way in Fig. 2, emphasizing the safety and maintenance aspects. Plant safety is inherent in an accelerator (or hybrid multiplying target) system, but we have already addressed the safety and fault-shutdown systems in some depth for the ERAB review. Likewise, maintenance depends on very low beam losses along the accelerator and beam transport lines. Perhaps time permits a brief comparison of the characteristics of the proposed 250 mA machine to the most intense machine now operating – the 1 mA average current LAMPF accelerator.

Fig. 3. indicates the advanced high brightness, high-energy linac capabilities resulting from almost 20 years of development since LAMPF became operational. Comparisons include:

- APT utilizes an RFQ preaccelerator.
- Low energy end of APT is at higher frequency -- better performance on fundamental beam physics grounds.
- APT transition energy to CCL is at lower energy, followed by possible emittance filter, to keep maximum brightness.
- APT frequency transition is only a factor of two, rather than four, easing the longitudinal transition.
- All rf buckets are filled in APT – gives factor of four in average current with no further stress on CCL design..
- Peak current of APT is well below current limit in each section. Number of particles per bunch only 4.4x that of LAMPF; thus extrapolation in current is not large.

End-to-end simulations have been done for this design, including effects of non-ideal conditions -- the emittance performance is shown in Fig. 4, along with the rf power requirements.

The design philosophy is summarized in Fig. 5.

Key issues that were taken into account are listed in Fig. 6.

We have compared measured emittance growth with predictions from simulation for LAMPF, CERN, and ATS; and compare with the end-to-end simulation for APT as shown in Fig. 7

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Beam losses at LAMPF have been analyzed in Fig 8. LAMPF pulses at 120 pulses per second - there are losses at the beginning of each pulse that are 2-3 times the losses during the steady-state part of the pulse. Integrated dose is observed to be about three times higher for the turn-on adjustment phase as compared to stable operation. A cw accelerator should have an improvement by about a factor of three over a pulsed machine.

Fig. 9 summarizes the APT activation estimate obtained by scaling from LAMPF operating conditions.

Fig. 10 compares beam losses and activation levels for LAMPF and APT at 800 MeV.

The nonlinear beam expander system would be used in APT to provide a 4m by 2m area at the target, with little beam outside that area, as shown in Fig. 11. Nonideal situations have been studied, as have various failure modes, and design steps can be taken to cope with these.

Acknowledgements

References

1. "Accelerator Production of Tritium", ERAB Review, October 25, 1989, Los Alamos National Laboratory

Figures

Fig. 1. Schematic of a system for Accelerator Production of Tritium (APT).

Fig. 2. Block diagram of an intense, high-energy linac, emphasizing safety and maintenance aspects; these require special design of the accelerator and target systems, and excellent diagnostics and control capabilities.

Fig. 3. Evolution of high-brightness linac capability since LAMPF.

Fig. 4. APT reference accelerator configuration.

Fig. 5. Design philosophy for high-brightness linear accelerators.

Fig. 6. Key issues in accelerator facility design.

Fig. 7. Transverse emittance growth in high-current linacs -- comparison of measurements with simulation.

Fig. 8. Estimated beam loss in LAMPF CCL for 1 mA average current operation.

Fig. 9. Procedure for scaling from LAMPF operating conditions to get activation estimate for higher brightness machine. The APT design has 4.4 times more particles-per-bunch than LAMPF. The "x4" in the figure is approximate.)

Fig. 10. Actual beam losses, activation levels, and aperture/beam ratio for LAMPF, with estimate for APT linac.

Fig. 11. Beam delivery to APT target.

Fig. 1. Schematic of a system for Accelerator Production of Tritium (APT).

| Safety | Maintenance |

| Injector | RFQ | DTL | CCL | Transport | Target |

| Diagnostics | Control Automation | RF Power |
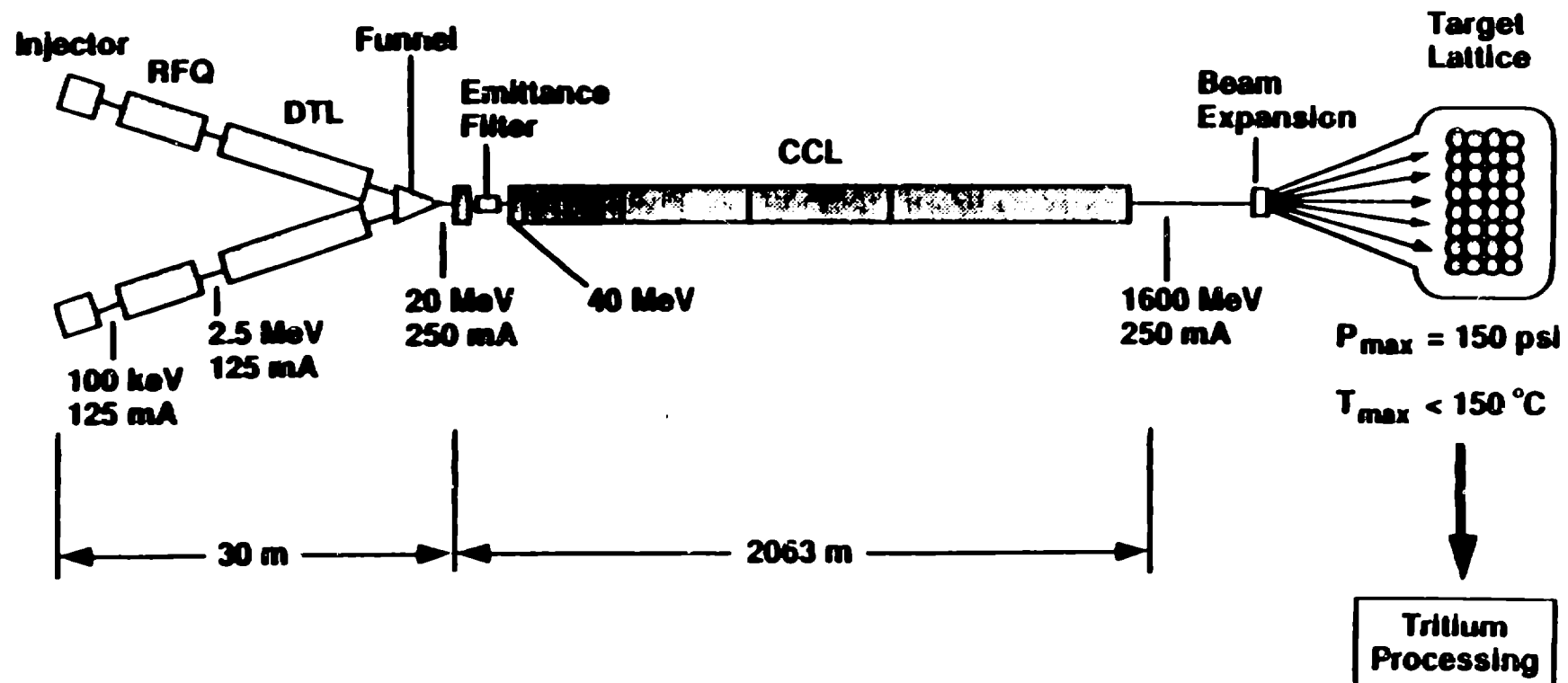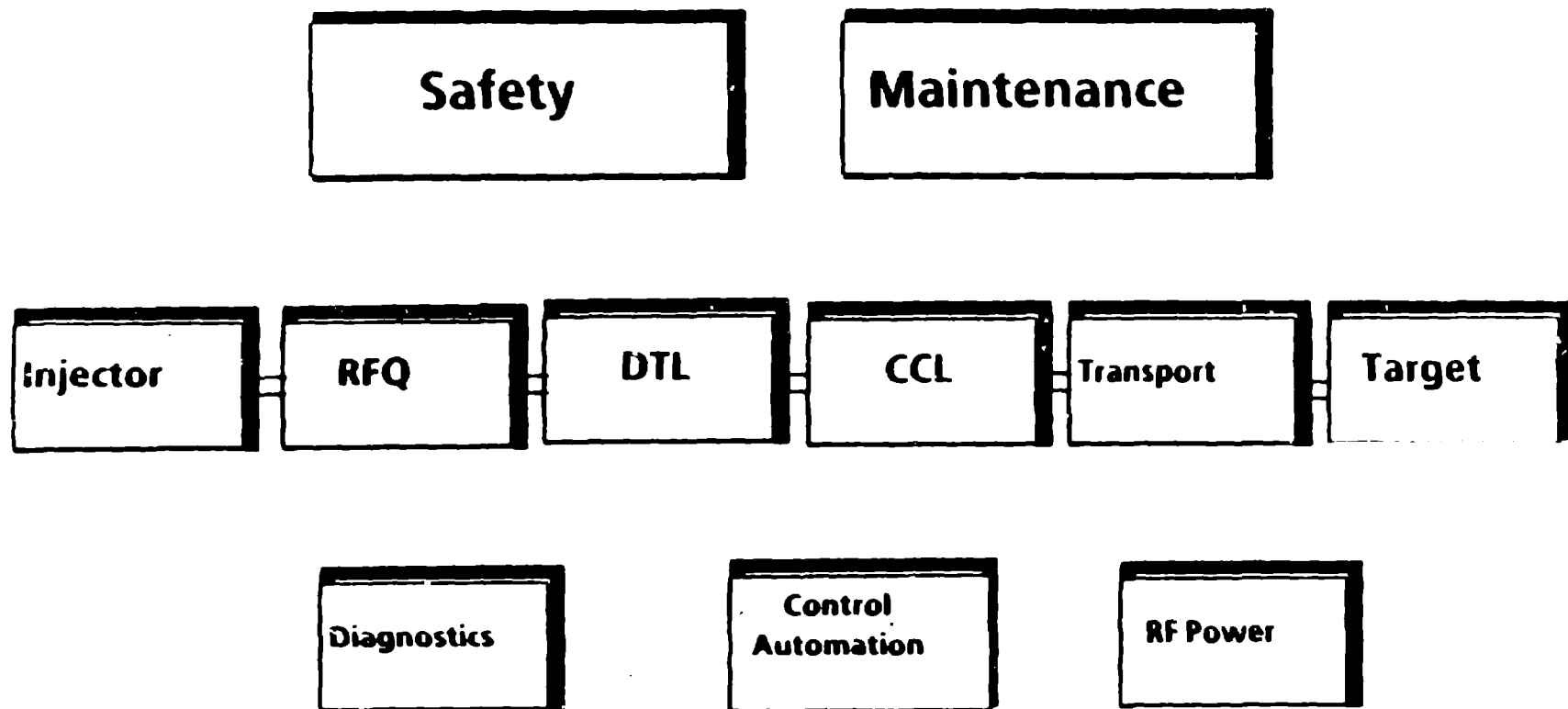
RFQ — Radio Frequency Quadrupole
DTL — Drift Tube Linac
CCL — Coupled Cavity Linac

Fig. 2. Block diagram of an intense, high-energy linac, emphasizing safety and maintenance aspects; these require special design of the accelerator and target systems, and excellent diagnostics and control capabilities.
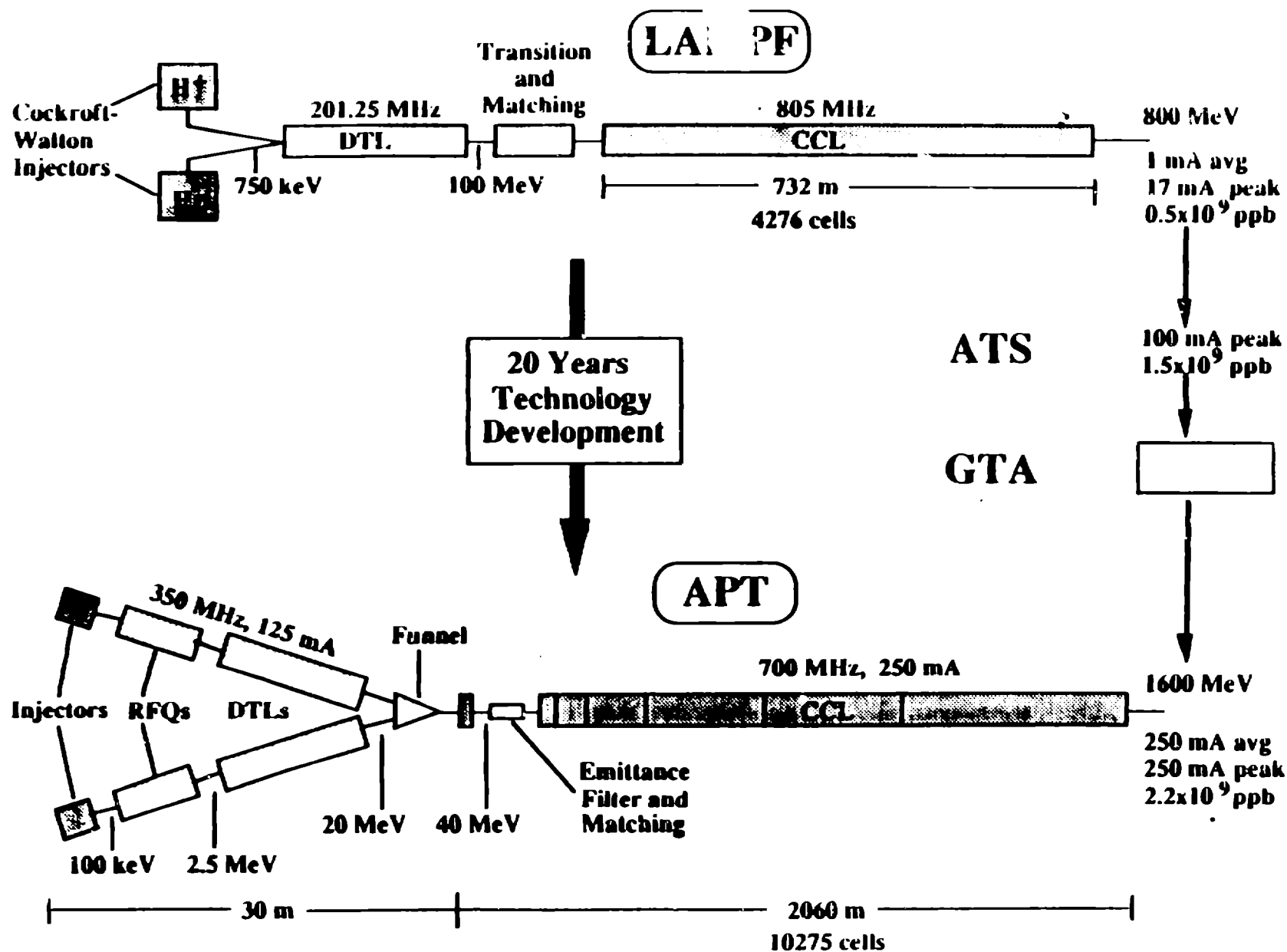
Fig. 3. Evolution of high-brightness linac capability since LAMPF
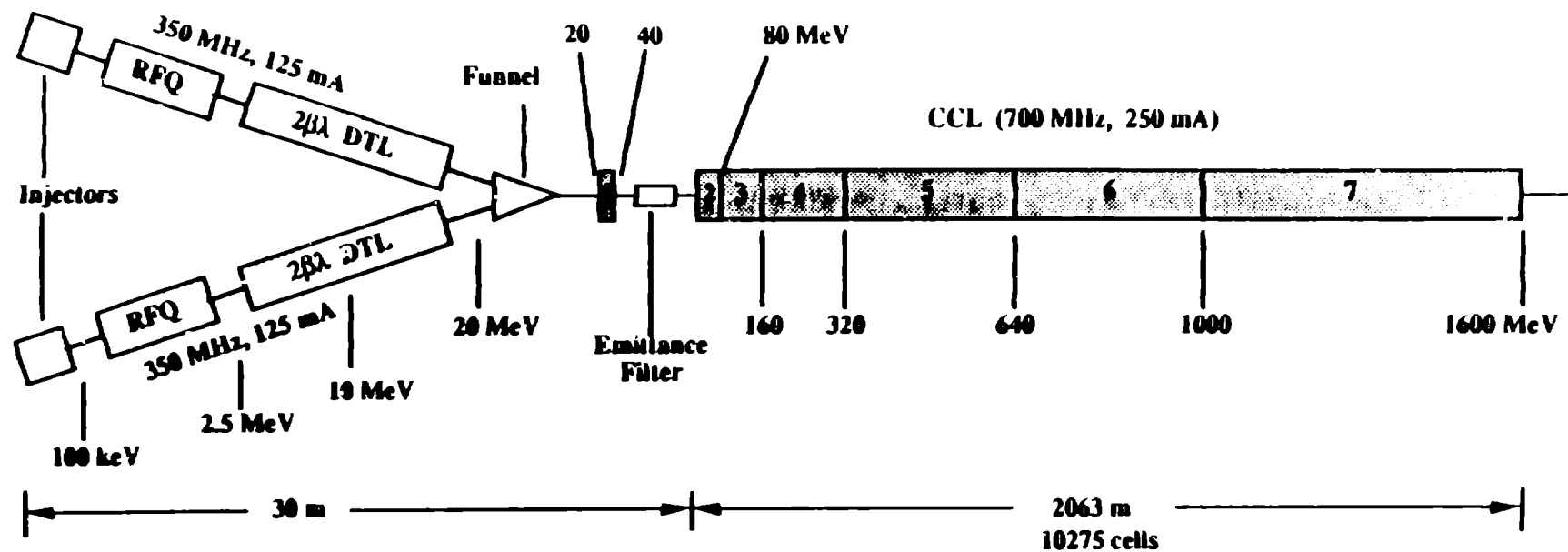
	Length (m)	RF Power (MW)			No. Tubes	Trans. Emittance* (π cm-mrad)		Long. Emittance* (10^{-6} π eV-sec)	
		Copper	Beam	Total		Input	Output	Input	Output
RFQ	3.4	0.4	0.3	0.7	2	0.020	0.023	0.0	1.4
DTL	11.3	1.3	2.2	3.5	10	0.024	0.061	1.5	2.9
CCL	2063	114.8	395.0	509.8	470	0.061	0.068	2.9	4.4
Total	2100	118.2	400.0	518.2	482				

Total AC Power for Accelerator = 910 MW   * Emittance values are for non-ideal beam.

Fig. 4. APT reference accelerator configuration.

Fig. 5. Design philosophy for high-brightness linear accelerators.

Main Design Objectives:

1. <u>High beam transmission and low losses</u>
   Minimize resultant heating and activation of accelerator components

2. <u>Unit cost, efficiency, and reliabiliy of rf tubes</u>

- **Establish good beam quality at the low energy end to minimize beam emittance and halo (RFQ, funneling, ramped DTL, high frequency)**

- **At higher energies keep beam away from apertures and longitudinal bucket limits (large aperture, large bucket, good alignment, good phase control, low accelerating gradient)**

- **Employ extensive diagnostics for beam control and maintenance of acceptable operating regime**

- **Some halo and spill may still occur but activation effects can be limited (rad-hard quads (sets upper limit on DTL frequency), restrict transitions, emittance filters)**

Design front end to launch high quality, low-halo beam.
Design CCL for ultra-low beam loss and high rf efficiency.

Fig. 6. Key issues in accelerator facility design.

There are many issues when considering operation of a production factory

- **Code validity** — basis of accelerator design
- **Beam losses** — heating and activation
- **Maintenance, failures** — scheduled program and estimates
- **Reliability, safety** — operating regimes, restrictions, and procedures
- **Remote operation** — experience and equipment
- **Accelerator factories** — experience at operational facilities
- **Factory operation** — procedures for turn-on, turn-off, and monitoring
- **Power** — load characteristics
- **"Burps"** — characteristics of microdischarges
- **Instabilities** — design conservative

Fig. 7. Transverse emittance growth in high-current linacs -- comparison of measurements with simulation.

	LAMPF DTL + CCL	CERN DTL	CERN DTL	ATS-1 [a] RFQ+DTL	ATS-2 [b] RFQ+DTL	APT RFQ+DTL+CCL
Output Energy (MeV)	800	10	50	5	6.7	1600
Peak Current (mA)	17	82	150	75	75	250
Particles per Bunch	0.53×10^9	3.3×10^9	4.6×10^9	1.1×10^9	1.1×10^9	2.2×10^9
Transverse Emittance: Growth (Simulation)	8.7 (ideal)	1.2 (ideal)	1.1 (ideal)	2.5 (realistic)	1.6 (realistic)	1.5 (ideal) 3.4 (non-ideal)
Growth (Measured)	7.9	1.9	2.9	3.5 ± 0.35	1.8 ± 0.18	---
Output (Measured)	0.070	0.070	0.14	0.060 ± 0.006	0.030 ± 0.003	---

a. Uniform-field DTL ($E_0 = 2$ MV/m). Results quoted are from 1989 measurements. Majority of emittance growth is caused by quadrupole-orientation errors in drift tubes.
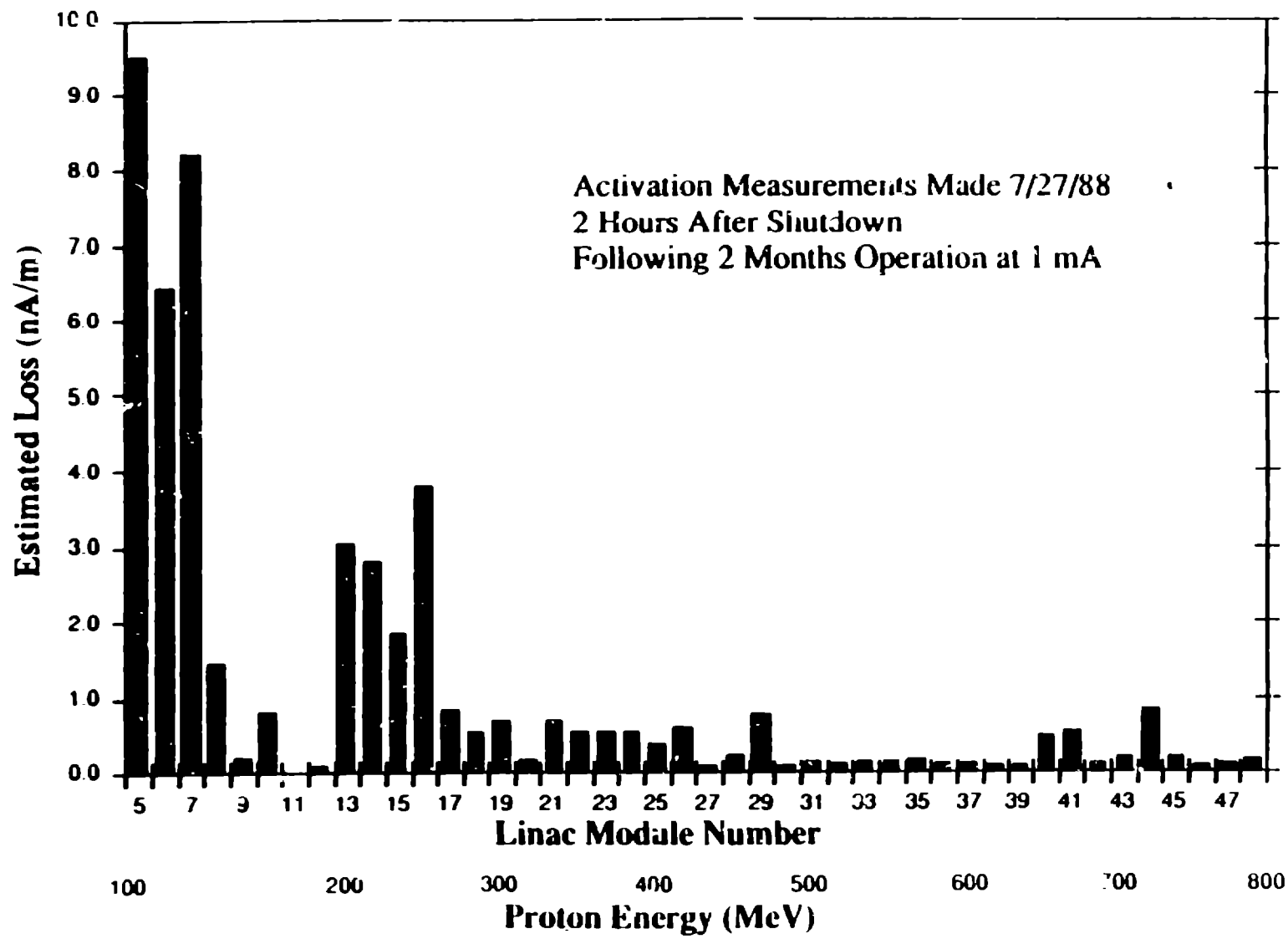
b. Ramped-field DTL ($E_0 = 2$ to 4 MV/m).

Fig. 8. Estimated beam loss in LAMPF CCL for 1 mA average current operation.

- Extend LAMPF to 1) cw operation and 2) fill all 805-MHz rf buckets.
- No increase in protons/bunch (identical beam dynamics).
- Linac current and activation would increase by factor 60.
    - x 15 from duty-factor increase
    - x 4 from filling rf buckets
- Average current would be almost 25% of APT design goal.
- Activation levels would be 50 to 200 mRem/h.
- **Hands-on maintenance**, although with limited access time.

* Linac design improvements permit x 4 increase in particles-per-bunch without increased beam loss.

Hands-on vs Remote Maintenance

| **10 mRem/h and below** | Unconstrained hands-on maintenance. |
100 mRem/h	Hands-on maintenance; limited access time.
1 Rem/h	Hands on maintenance with carefully controlled, very-limited access.
10 Rem/h and above	Remote maintenance required.

Fig. 9. Procedure for scaling from LAMPF operating conditions to get activation estimate for higher brightness machine. The APT design has 4.4 times more particles-per-bunch than LAMPF. The "x4" in the figure is approximate.)

	LAMPF	APT
Activation (mRem/h)	4*	100
Beam loss (nA/m)	0.2	5
Fractional loss /m	2×10^{-7}	2×10^{-8}
Aperture/beam RMS	6.3	20

* Except for a few hot spots

APT needs 10 times lower fractional loss /m than LAMPF to retain hands-on maintenance. A factor of 100 should be achievable.

* APT has factor of 2 to 3 advantage because it is not a pulsed machine.

* Need additional factor of 5 to 3 from large aperture/beam-RMS ratios. We believe that much larger factors will be attainable.

Fig. 10. Actual beam losses, activation levels, and aperture/beam ratio for LAMPF, with estimate for APT linac.

**Gaussian Beam Profiles
Upstream of Beam Expander**

X(CM)

Y(CM)

Beam Profiles at APT Target
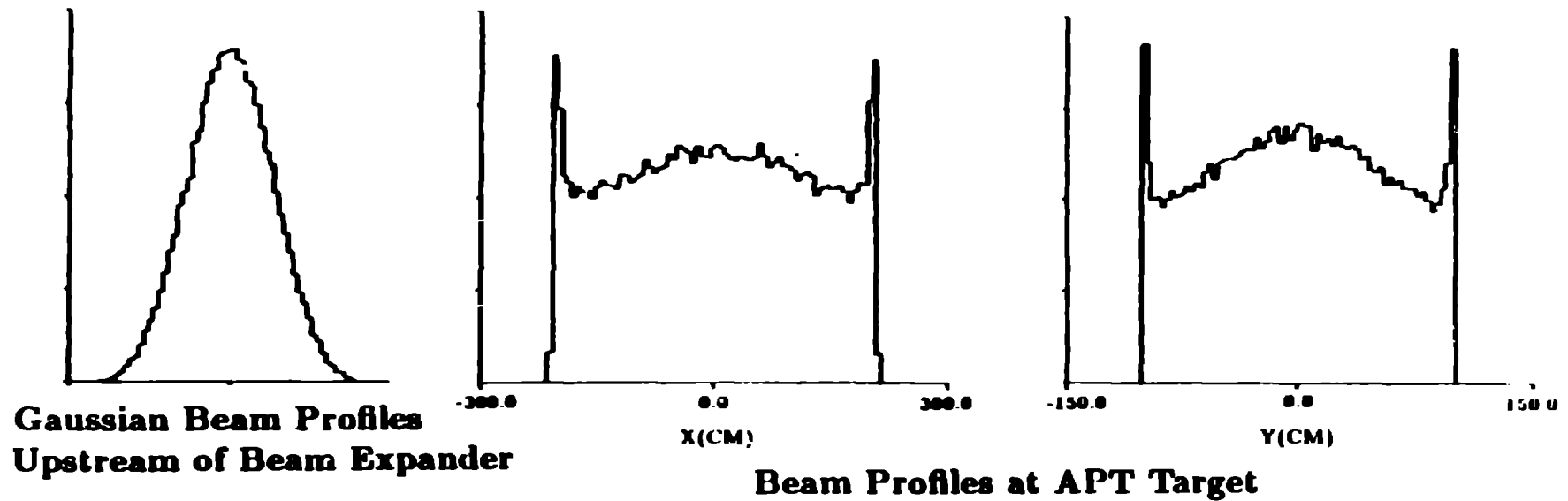
- Beam at target has desired 4m by 2m area.

- Sharp drop to very small intensities outside the 4m by 2m area when duodecapoles are off.

- Halo to 7σ contained in the 4m by 2m area when duodecapoles are on.

- Above statements true regardless of initial beam profiles.

- Intensity distribution within the 4m by 2m area very uniform for initially parabolic beams.

but:

- Intensity distribution within the 4m by 2m area depends on initial beam profiles.

- Intensity distribution within the 4m by 2m area depends on steering.

Fig. 11. Beam delivery to APT target.